The magnetic remanence of hematite-bearing murals

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Magnetic remanence of hematite-bearing murals

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[1] We report on a series of experiments designed to test the ability of hematite-bearing colors to record the direction of the ambient magnetic field. Plasterboards accurately oriented with respect to the Earth's magnetic field were painted with red tempera colors prepared with hematite pigments. Magnetic measurements indicate that the color film retains a remanent magnetization and acquires a well developed magnetic fabric. The remanence direction is close to, yet slightly deviated from the Earth's magnetic field. The deviation is interpreted to result from preferential alignment of the pigment grains parallel to the plasterboard surface and depends on both its orientation with respect to magnetic north and the degree of magnetic anisotropy of the color film, which in turn varies according to the pigment used. Investigation of the magnetic remanence of murals may complement archaeomagnetic information derived from traditional materials such as baked and fired structures.

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1. Introduction

[2] Red colored, hematite-bearing mural paintings have been shown to carry a remanent magnetization close to the geomagnetic field direction at the time they were painted, known either from direct historical measurements [*Chiari and Lanza*, 1997, 1999] or archaeomagnetic data [*Zanella et al.*, 2000; *Goguitchaichvili et al.*, 2004].

[3] The basic model for acquisition of a pictorial remanent magnetization (PiRM) supposes that when the color is applied to a wall, the hematite grains behave as tiny magnets free to move and align their moment parallel to the Earth's field. Once the color dries, the grains are locked and magnetization is preserved over time. This model was tested in laboratory controlled conditions: colors were prepared with high-quality pigments and used to paint oriented plasterboards. The natural remanent magnetization was measured and its direction checked against that of the laboratory field. A deeper understanding of the remanence characteristics was obtained from measurement of the anisotropy of isothermal remanent magnetization (AIRM). Measurements were done at the ALP laboratory (Peveragno, Italy) using a JR-6 spinner magnetometer, a 2-G Enterprises degausser, a Molspin AF demagnetizer, a Bussi pulse magnet and a Schonstedt thermal demagnetizer.

2. Samples and Remanence Measurements

[4] Two red colors were prepared using a 4 to 1 mixture of water and egg yolk as binder (90% in volume) and commercial hematite pigments (10%), namely *Morellone* and *Rosso di Marte* (Zecchi, Fine art and restoration materials – Firenze), which are equivalent to the pigments with the same names used by Italian Renaissance painters. Scanning Electron Microscope (SEM) images (Figure 1) demonstrate that the grain size of both pigments is less than 0.5 μm and that the *Morellone* grains are mostly flake-shaped, and that the *Rosso di Marte* ones are acicular. The colors were applied to plasterboards placed in grassland opposite the laboratory, in order to avoid any unevenness of the magnetic field inside the building. The plasterboards were accurately oriented with respect to the Earth's magnetic field using bubble levels, a compass and a 3-axes fluxgate magnetometer. Orientation accuracy was estimated as $\pm 1°$. Samples were taken with the flexible plastic disk (φ = 18 mm) technique [*Chiari and Lanza*, 1999; *Goguitchaichvili et al.*, 2004]. In order to make possible thermal demagnetization of the color film, one basal face of oriented standard cylindrical paleomagnetic specimens (φ = 25.4 mm, h = 23 mm) was also painted. To avoid any bias in measuring the PiRM, diamagnetic limestones were used and the possible remanence carried by incidental ferrimagnetic grains was checked before painting. The measured signal was of the order of 10^{-11} Am^2, similar to the nominal sensitivity ($2.6 \cdot 10^{-11}$ Am^2) of the JR-6 spinner magnetometer.

[5] Magnetometers used in paleomagnetism are designed to measure specimens usually 8 to 11 cm^3 in volume, whereas the disk-shaped specimens of color film are some tens of microns thick and a few cubic millimeters in volume. The result of a measurement might therefore depend on the position of the specimen relative to the pick-up coils of the spinner magnetometer. To check this possible effect, two groups of ten specimens were measured in two positions. In the first one, the diameter of the disk coincided with the spinner axis, while in the second the disk was shifted 10 mm sideways. The group mean directions are statistically indistinguishable (Table 1), which suggests that the small, 1° to 3°, differences between the directions of individual specimens reflect random errors probably due to the positioning of specimens within the spinner specimen holder.

[6] Six vertical plasterboards with different orientations with respect to magnetic north were painted. The azimuths, measured clockwise, were: 0°, 30°, 45°, 90°, 315° and 330°. Various portions of individual plasterboards were painted with different brushstroke orientation: up-down, side to side, random. Ten specimens for each color were collected from each plasterboard. They were measured and the mean direction of each group was calculated using *Fisher* [1953] statistics. The painting always acquired a remanent magnetization with magnetic moment in the order of $3-6 \times 10^{-9}$ Am^2 and directions tightly grouped. The angular dispersion was usually smaller for *Morellone*

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Table 1. Mean PiRM Direction and Intensity for *Morellone* Specimens From Plasterboards With Different Orientations and Measured in Different Positions Within the JR-6 Coils[a]

Azimuth	Position	n	D, I (deg)	M (Am^2)	k	α_{95} (deg)
30°	Central	10	2.7, 57.3	4.3 10^{-9}	318	2.7
30°	Offset	10	4.5, 57.0	4.3 10^{-9}	544	2.1
330°	Central	10	358.3, 58.4	3.3 10^{-9}	118	4.5
330°	Offset	10	359.7, 59.2	3.3 10^{-9}	148	4.0

[a]Key: azimuth: plasterboard orientation; position: position of the specimen within the measuring coils; n = number of specimens; D, I = declination, inclination; M = magnetic moment; k, α_{95} = precision, semi-angle of confidence from *Fisher* [1953].

($0.8° \leq \alpha_{95} \leq 2.7°$) than for *Rosso di Marte* ($2.4° \leq \alpha_{95} \leq 5.1°$). The directions were not affected by the brushstroke orientation and close to that of the local ambient field (D = 0°, I = 59°), although small differences (0° to 9°) in declination were detected (Figure 2). The differences look systematic because the value of the deviation angle is a function of the azimuth of the plasterboard and the deviation is opposite in sense to the plasterboard orientation: it is clockwise when the plasterboard azimuth falls in the NE-SW quadrant, and counterclockwise when in the NW-SE quadrant. One horizontal plasterboard was painted and the inclination of the painting remanence was 6° to 12° shallower than that of the ambient field. The possible origin of the observed deviations is discussed below.

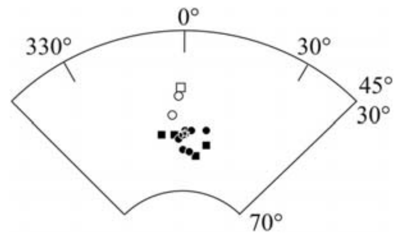

Figure 2. Equal-area projection of the PiRM directions from plasterboards painted with *Morellone* (circles) and *Rosso di Marte* (squares) pigments. Full/open symbols: vertical/horizontal plasterboards; star = laboratory ambient field.

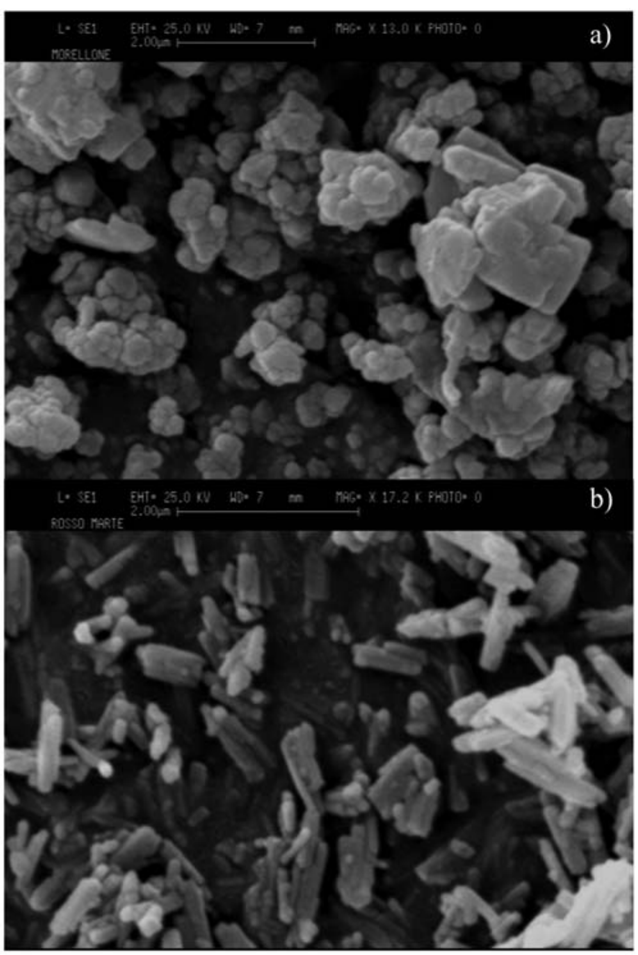

Figure 1. SEM images of (a) *Morellone* and (b) *Rosso di Marte* pigments.

3. Characteristics of the Acquired Remanence

[7] The PiRM stability is good, which is typical of remanences carried by powdered hematite. The PiRM direction does not change throughout stepwise thermal and AF demagnetization. More than 50% of the initial remanence is still present after heating at 580°C, and some 60% remains after AF demagnetization at a 280 mT peak-field. Similar observations were made for some murals at the Bibliotheca Apostolica in Rome [*Chiari and Lanza*, 1999]. This demonstrates that hematite-bearing mural paintings carry a stable record of the Earth's field at the time they were painted and may be used in archaeomagnetic studies, as in the case of Pompeii [*Zanella et al.*, 2000].

[8] The observed deviation of the remanence direction from the ambient field needs further investigation. The inclination shallowing in the case of the horizontal plasterboard might be regarded as analogous to that typical of a depositional remanent magnetization (DRM). Preferential orientation of non-equant detrital grains is caused by gravity in the DRM case, whereas in the PiRM one it could be caused by other phenomena acting on the pigment grains, such as surface tension in the color films, which parallels the painted surface, or grain anisotropy in the hematite pigment.

[9] Vertical plasterboards give a clue to understand the deviation. Let β be the angle between magnetic North and the azimuth of the plasterboard (Figure 3) and δ the angle between the plasterboard and the PiRM horizontal component. Should the PiRM direction coincide with magnetic North, $\delta = \beta$. The fact that $\delta \leq \beta$ means that the PiRM direction is systematically deviated toward the painted surface and that it does not coincide with magnetic North. The systematic deviation may be accounted for by preferential orientation of the pigment grains, which would tend to orient their long dimension parallel to the color film, namely to the painted surface. The easy magnetization direction of hematite lies in the lattice basal plane, whereas the hard direction parallels the axis of symmetry. The long dimension of hematite grains usually corresponds to the basal plane so that their preferential orientation would bias the remanence direction. This hypothesis can be tested by investigating the magnetic fabric of the color film by means of remanence anisotropy measurements. AIRM was thus

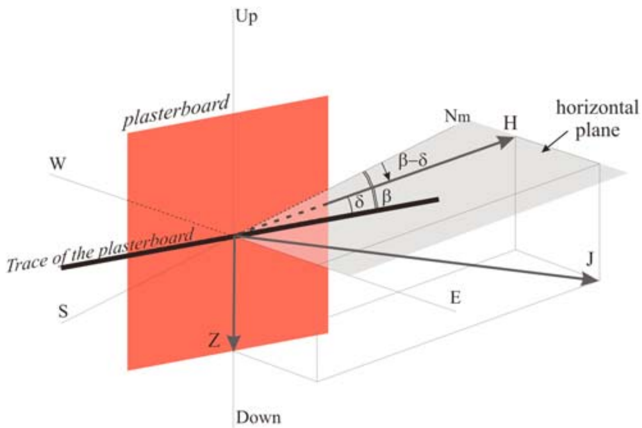

Figure 3. Geometrical sketch of a hypothetical PiRM vector and plasterboard orientation. Symbols: Nm = magnetic North; J = PiRM vector; H, Z = PiRM horizontal and vertical components; β = plasterboard azimuth; δ = angle between plasterboard and H; $\beta - \delta = \Delta$, declination error.

measured on specimens from vertical and horizontal plasterboards. The specimens were subjected to tumbling AF demagnetization in the maximum available peak-field of 100 mT and were then given a direct field of 80 mT for the *Morellone* and 60 mT for the *Rosso di Marte* specimens. IRM acquisition curves showed that these values were enough to give the specimens a magnetic moment in the order of 1×10^{-7} Am^2. The procedure was repeated twelve times: the direct field was applied in six different positions according to the scheme of *Jelinek* [1996], and in two opposite directions for each position, in order to cancel the NRM component harder than 100 mT. The magnetic fabric is similar in all specimens and is always well developed. The minimum axes I_3 are well grouped and are orthogonal to the plasterboard plane (Figure 4), which coincides with the magnetic foliation; the maximum I_1 and intermediate I_2 axes are more or less dispersed within the foliation plane. The anisotropy degree, $P = I_1/I_3$, is higher for the *Rosso di Marte* specimens (P = 1.55) than for the *Morellone* (P = 1.18) specimens.

[10] According to *Uyeda et al.* [1963] the relationship between the actual direction of the remanence and that of the external magnetizing field is (using our symbols from Figure 3) $\tan\delta = 1/P \tan\beta$, where P is the degree of anisotropy. Experimental values of $\tan\delta$ vs. $\tan\beta$ (Figure 5a) have good linear correlation; interpretation of the *Morellone* curve using the above equation gives a calculated value P = 1.14, which is consistent with the experimental value of P = 1.18, whereas the agreement is less good for the *Rosso di Marte* specimens, whose calculated and experimental values are P = 1.27 and P = 1.55, respectively. The equation of *Uyeda et al.* [1963] may thus be used to calculate the

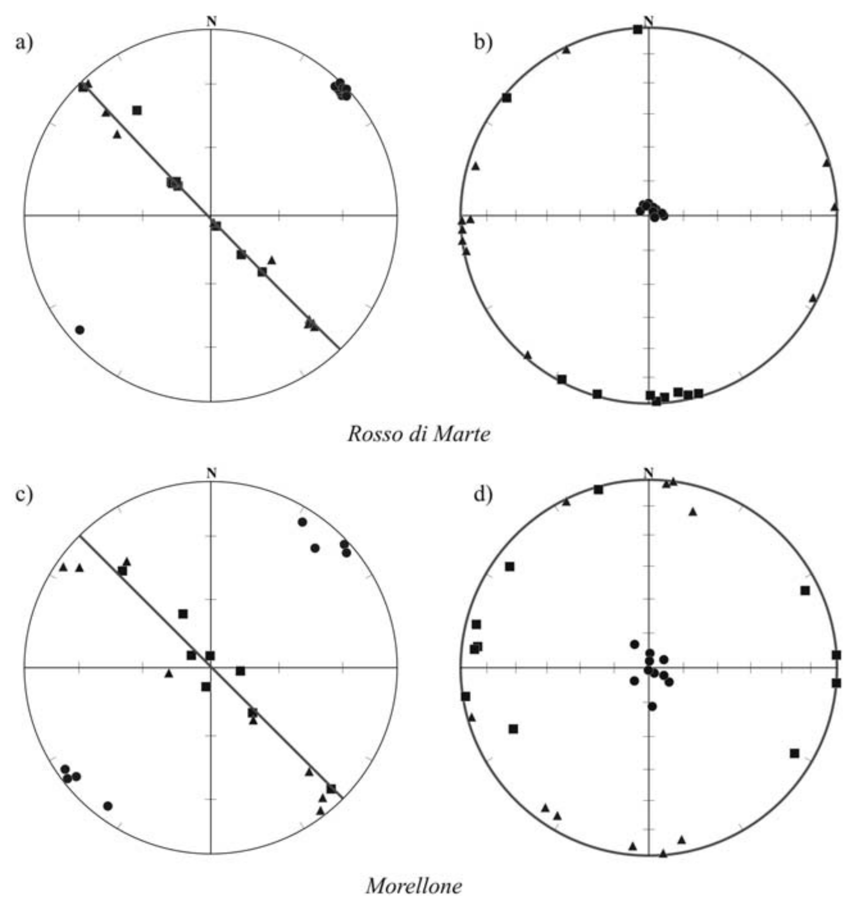

Figure 4. Equal-area projection of AIRM principal directions: (a, c) vertical plasterboards; (b, d) horizontal plasterboards. Symbols: squares = maximum axis, I_1; triangles = intermediate axis, I_2; solid circles = minimum axis, I_3; thick great circles = magnetic foliation.

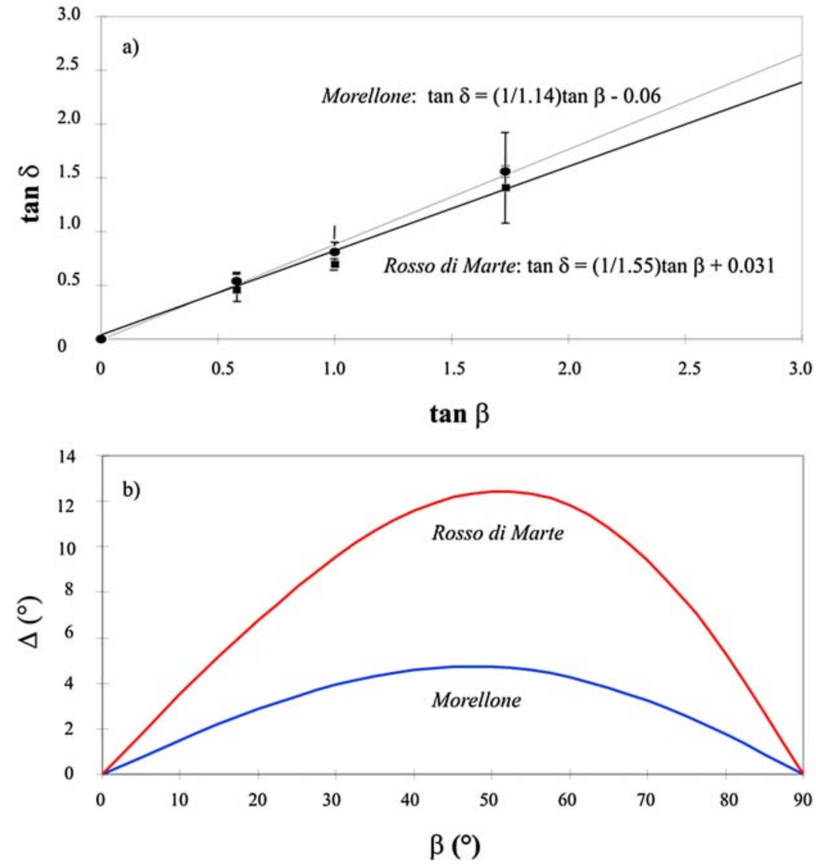

Figure 5. (a) Tangent of PiRM declination (δ) vs. tangent of plasterboard azimuth (β) measured from magnetic North (see Figure 3 and text for further explanation). Symbols: solid circles = *Morellone* (r = 0.997) specimens, and squares = *Rosso di Marte* (r = 0.976) specimens. (b) Calculated PiRM declination error $\Delta = (\beta - \delta)$ as a function of wall orientation (β).

PiRM declination error $\Delta = \beta - \delta = \beta - \tan^{-1}$ (1/P tan β) (Figure 5b), i.e. the expected deviation of the PiRM from the geomagnetic field.

[11] Since the deviation is clockwise or counterclockwise according the wall azimuth is in the NE or NW quadrant, its effect on the mean PiRM direction derived from different walls in the same building is strongly reduced. Paleomagnetic directions for murals sampled from the four walls of a room at Palazzo Venturi-Gallerani (Siena, Italy), which were painted in 1794, are slightly different (Figure 6), yet their mean (D = 341°, I = 65°) is indistinguishable from the coeval Earth's magnetic field direction (D = 343°, I = 64°) from direct historical measurements [*Cafarella et al.*, 1992].

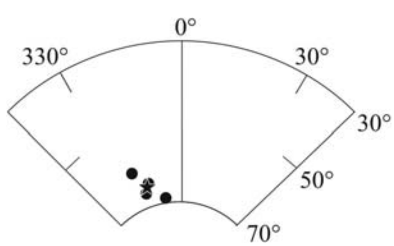

Figure 6. Equal-area projection of the PiRM directions from murals painted on the four walls of a room at Palazzo Venturi-Gallerani (Siena, Italy). Symbols: solid circles = individual mural mean PiRM direction; star = Earth's magnetic field direction from historical measurements in 1794.

[12] The equation of *Uyeda et al.* [1963], written in the form tan I_{DRM} = 1/P tan I_{Field}, is often used to estimate inclination shallowing in sedimentary rocks,. In the case of horizontal plasterboards, the equation works well in the case of the PiRM carried by *Rosso di Marte*, and gives the same shallowing (12°) as the observed value. The calculated shallowing in the *Morellone* (5°) case is close to or half of the observed values (6° and 10° respectively).

4. Discussion and Conclusions

[13] On the basis of the experimental results, we conclude that the PiRM direction acquired by a mural painting is a stable remanence whose direction is slightly deviated from that of the Earth's magnetic field as a function of the wall orientation and the degree of magnetic anisotropy of the color film. In terms of archaeomagnetic investigations, the deviation of the PiRM direction relative to the ambient field does not imply that murals are unreliable sources of information on secular variation (SV). On the one hand, the deviation is zero for walls oriented N-S or E-W. On the other, the expected deviation may be evaluated from AIRM measurements. Moreover, since the error depends on the wall orientation, it may be cancelled by sampling different walls in the same room or building and calculating the mean PiRM direction. In conclusion, our simple model for PiRM

acquisition appears to work well enough for archaeomagnetic purposes. Investigation of new types of materials, such as mural paintings and plasters [*Soler-Arechalde et al.*, 2006], extends the use of archaeomagnetism beyond the traditional baked and fired structures and provides new opportunities to date archaeological finds.

[14] **Acknowledgment.** The authors are indebted to G. Chiari for providing the samples from the Palazzo Venturi-Gallerani murals.

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